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Enhancing soil carbon stocks and soybean yields in coastal areas through the application of biofertilizers

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ABSTRACT

Climate change driven by increased concentration of greenhouse gases in the atmosphere has a significant impact on agricultural systems, particularly in coastal areas that are prone to rising salinity and decreased soil quality. The application of biofertilizers as a strategy for enhancing soil carbon stocks is crucial, given their role in promoting microbial activity and nutrient availability, leading to soil fertility. This study aimed to evaluate the role of biofertilizers in increasing soil carbon stocks and soybean yields in coastal areas. The research was conducted from April to December 2024 in Bengkulu City. The field experiment was designed in a split-plot design, with the main plot was soybean varieties at two levels (i.e., Anjasmoro and Dering I), and the subplot was fertilizer inputs at four levels (i.e., recommended inorganic fertilizer, AMF + Bradyrhizobium + potassium solvent, Bradyrhizobium + phosphate solvent + potassium solvent, and Bioenzyme). The application of biofertilizers and bioenzymes effectively increased soil carbon stock. The potassium-solubilizing microbial population had a greater influence on carbon stocks than the phosphate-solubilizing population and AMF. The use of biofertilizers and bioenzymes also improved soil biological properties and nutrient absorption, thereby contributing to increase soybean yields. This study provides evidence to support government policies promoting biofertilizer use in agriculture, including training and extension programs for farmers, particularly in coastal areas, to improve soil quality, enhance yields, and reduce dependence on chemical fertilizers which are often expensive and can degrade soil quality in the long term.

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1. INTRODUCTION

Coastal areas have a potential for agricultural development to support both local and national food supply, especially in Bengkulu, Indonesia. However, agricultural expansion in the coastal areas will face limiting factors, primarily low levels of soil fertility. Coastal areas tend to be less fertile due to high evapotranspiration, low groundwater content, very low cation exchange capacity, low organic and organic carbon content, low soil nitrogen, and high salinity levels influenced by seawater (Bertham et al., 2019). Thus, agricultural development along the coastal belt has to adopt appropriate cultivation technology to increase soil fertility. However, misuse of cultivation technology that is not even environmentally friendly has the potential to create other issues, like extra carbon emissions.

Carbon emissions are vapors emitted through the combustion of any carbon-containing materials, such as carbon dioxide (CO_2), diesel, gasoline, liquefied petroleum gas, and others. Carbon emissions are the process of releasing carbon into the Earth's atmosphere. Agriculture is one among the activities producing greenhouse gases in the air (Chataut et al., 2023; Zhong et al., 2022) and these greenhouse gases particularly CO_2, CH_4, and N_2O, are increasing globally (Shakoor et al., 2021). Carbon emissions are one of the primary drivers of climate change and global warming (Ariani et al., 2021). However, in addition to being one of the sectors that contributes to climate change, the agricultural sector is also significantly impacted by its effects (Akmalia, 2022; Keutgen, 2023). One of the significant impacts is the

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alteration of the dry and rainy season cycles, as well as changes in rainfall patterns. Both of these changes will lead to a high potential for crop failure (Guo et al., 2022). In addition, farmers will find it difficult to determine when to start planting due to the uncertainty of the dry and rainy seasons. Therefore, the step to reduce carbon emissions becomes very important in maintaining environmental balance.

The use of biofertilizer can be an effective method of reducing the carbon emissions created by the farming sector. Biofertilizer inoculum is a healthy means of increasing the yield of a crop while reducing the consumption of chemical fertilizers that are detrimental to human health. Biofertilizers perform a variety of functions, such as fixation of nutrients, synthesis of hormones, enzyme synthesis, and antibiotic synthesis (Sreethu et al., 2024). Biofertilizers play a crucial role in preserving ecological balance and regulating biogeochemical cycles, particularly by influencing the dynamics of key greenhouse gases (Whalen et al., 2022). Soil microorganisms are essential to these cycles, especially in processes like carbon sequestration and nitrogen fixation, which enhance soil fertility and contribute to long-term agricultural sustainability. By stimulating microbial activity, biofertilizers facilitate the conversion of atmospheric CO_2 into stable organic carbon within the soil, thereby mitigating greenhouse gas emissions. Furthermore, the effective management and strategic application of biofertilizers can optimize soil microbial communities, leading to the ecological intensification of agricultural systems. By stabilizing soil carbon and promoting plant growth across diverse environmental conditions, biofertilizers serve as a sustainable alternative to conventional chemical fertilizers, ensuring both improved agricultural productivity and environmental resilience (Buragohain et al., 2019; Mason et al., 2023).

Some of the microbes in soil with the ability to reduce rates of carbon emission in soybean cultivation in coastal areas include Bradyrhizobium, arbuscular mycorrhizal fungi (AMF), phosphate solubilizers, and potassium solubilizers. Mycorrhizal fungi and nitrogen-fixing bacteria with organic amendments have been known to sequester significantly higher amounts of carbon in plant and soil biomass. Natural mycorrhizae management improves soil organic carbon, hence improving soil quality and productivity (Ortas, 2022). Furthermore, previous research has also reported an increase in soil carbon stock due to the activity of potassium-solubilizing microorganisms (Jabin PP & Ismail, 2023; Sembiring & Sabrina, 2022) as well as phosphate-solubilizing microorganisms (Bertham et al., 2019).

Soil carbon stock enhancement is vital in climate change mitigation as it sequesters and locks away carbon dioxide (CO_2) from the atmosphere into soil organic matter. Apart from reducing greenhouse gas emissions, it also enhances soil quality, water retention, and sustainable agricultural productivity (Powlson & Galdos, 2023). Soils rich in organic carbon have a greater capacity to retain moisture and nutrients, thereby enhancing plant resilience to climate change, such as drought and land degradation (Minasny et al., 2017). Additionally, soil management that focuses on increasing carbon stock contributes to building a more stable ecosystem that is resilient to environmental disturbances (Don et al., 2024). By increasing the carbon sequestration capacity of soil, the approach can help reduce atmospheric concentrations of CO_2, slow the rate of warming worldwide, and support long-term climate change mitigation objectives (Mitchell et al., 2024).

The incorporation of soil carbon significantly influences soybean yield in coastal regions by improving the soil's properties. A higher organic carbon content enhances soil structure by promoting better aggregation, reducing soil compaction, and increasing porosity, which facilitates root penetration and aeration. Additionally, the improved soil structure leads to increased water-holding capacity, reducing the risk of drought stress and ensuring a more stable water supply for plant uptake, which is particularly crucial in coastal areas where fluctuating salinity levels and water scarcity pose significant challenges to crop productivity (Li et al., 2024). The presence of organic carbon also enhances nutrient retention by increasing the soil's cation exchange capacity (CEC), reducing nutrient leaching, and maintaining a balanced availability of essential nutrients. Furthermore, elevated soil carbon levels support a more dynamic and diverse microbial community, which plays a crucial role in organic matter decomposition, nitrogen fixation, and phosphate solubilization, thereby accelerating the release of nutrients essential for optimal plant growth and development (Chi et al., 2021).

This study offers a novel trend in integrating the use of biofertilizers as a strategy for resolving two main problems: increasing soil carbon sequestration and enhancing soybean yield in coastal areas. Many past studies have, to a large extent, encompassed the role of biofertilizers in plant productivity and soil fertility (Kumawat et al., 2023; Sadafzadeh et al., 2023), including through the increase of soil organic carbon levels, most studies have been limited to evaluating organic carbon content without further examining its contribution to soil carbon stock (Ding et al., 2024), especially in coastal environments with marginal soil characteristics. Yet, soil carbon stock plays a crucial role in ecosystem stability, long-term carbon storage, and climate change mitigation. The findings of this research are expected to provide new insights into the role of biofertilizers as a vital element in sustainable coastal agriculture, while also broadening understanding of how to manage marginal soils to support national food security. Therefore, this study aimed to evaluate the role of biofertilizers in increasing soil carbon stocks and soybean yields in coastal areas.

2. MATERIAL AND METHODS

The experiment was conducted from April to December 2024 in Beringin Raya Village (03˚45'23'' S, 102˚15'41'' E), Bengkulu City. The biofertilizer inoculum was prepared in the Soil Biology Laboratory, Faculty of Agriculture, University of Bengkulu. Soil and plant tissue analysis were conducted in the Soil Science Laboratory, Faculty of Agriculture, University of Bengkulu. All biofertilizer inoculants were isolated from coastal soils. Phosphate-solubilizing bacteria are cultured using Pikovskaya medium, while potassium-solubilizing bacteria are cultured using Alexandrov medium. Both bacteria exhibit clear zones on their respective media. The bacteria with the widest clear zones are then selected to produce inoculants using a carrier medium consisting of 90% compost, 7.5% activated charcoal, and 2.5% calcium carbonate. The experiment was designed using a split-plot design, with the main plot consisting of soybean varieties at two levels, namely Anjasmoro (V1) and Dering I (V2), while the sub-plot was fertilizer inputs at four levels, namely the recommended inorganic fertilizer (P1), AMF + Bradyrhizobium + potassium solubilizer (P2), Bradyrhizobium + phosphate solubilizer + potassium solubilizer (P3), and Bioenzym (P4). These treatments were repeated 4 times, giving 32 experimental units in total.

The experiment began with land clearing, followed by soil sampling. Soil samples were taken at five points and pooled to obtain a composite sample in order to analyze the original characteristics of the study area. After that, a plot of 1.5 m x 3 m was prepared using the hoes, with a 50 cm distance between plots and 100 cm between replications. Ten tons per hectare of coffee husk compost and 200 kg per hectare of dolomite were applied to improve soil conditions, followed by the application of 25% of the recommended dose of basic inorganic fertilizer. Urea (46% N) fertilizer was applied in two stages: half of the dose at planting and the remainder a month later, while triple superphosphate (44%-48% P_2O_5) and potassium chloride (60%-63% K_2O) fertilizers were applied all at once during the planting stage. The recommended inorganic fertilizer application is 75 kg per hectare of Urea, 100 kg per hectare of SP-36, and 100 kg per hectare of KCl (Ferayanti et al., 2020). Dissolve 10 ml of bioenzyme in 1 liter of water and spray evenly on the soil surface two days before planting to improve soil and plant performance. The bioenzyme dosage used is 7 liters per hectare, containing beneficial microorganisms such as nitrogen-fixing bacteria, root nodule bacteria, plant growth hormone producers, odor-reducing microbes, cellulose degraders, lignin degraders, and decomposers.

The plot was marked with planting holes using a wooden dibbler to a depth of about 5 cm before two soybean seeds were placed in each hole. The planting distance used was 30 cm x 30 cm, resulting in 50 planting holes per plot. The soybean seeds were inoculated with biofertilizers consisting of *Bradyrhizobium* before being sown in the plot. The inoculation was performed by mixing the seeds with a 40% gum powder adhesive. Additionally, phosphate-solubilizing and potassium-solubilizing bacteria were applied at a dose of 50 mg per plant, with a density of 3×10^6 CFU g^1. The AMF was also inoculated by adding 2.5 grams of inoculum to each planting hole to support plant growth. The inoculated AMF had a density of 15 AMF spores per zeolite carrier medium. After two weeks of sowing, the seedlings were thinned and left with only one seedling.

The plants were watered every evening except on rainy days because, in the afternoon, the air temperature begins to drop, allowing the water to be retained in the soil longer and absorbed more effectively by the plant roots. Weed control was carried out mechanically every two weeks until harvest. Pest and disease control was routinely conducted every two weeks by spraying soursop leaf extract. However, at 60 days after planting, an infestation of brown stink bugs occurred, requiring control using Curacron pesticide (active ingredient: profenofos) at a dose of 1 ml per liter. The harvesting process was conducted in two stages: the first harvest took place during the vegetative phase, at 40 days after planting, when 10% of the plants had begun flowering. The second harvest was carried out during the generative phase, once the fruit had dried and turned brown. During the first harvest, five plants were randomly selected from the middle of each plot. Additionally, a composite soil sample was collected using a cylinder ring from a soil depth of 15 cm in each plot for further analysis.

The observed variables were organic carbon content using the Walkley and Black method (Sahrawat, 1982) Potassium solubilizer population using Alexandrov growth media (Sun et al., 2020), phosphate solubilizer population using Pikovskaya growth media (Pikovskaya, 1948), AMF population using the wet sieving method (Pacioni, 1992), nutrient levels of nitrogen, phosphorus, and potassium in the tissue using the H_2SO_4 wet ashing method (van Lierop, 1976), dry weight of the plants, seed weight per plant, and dry seed weight per plot. The soil carbon stock was calculated using Equation 1 (Tadiello et al., 2022).

$$Cs = \frac{Cc \times BDxD}{10} \quad \text{.........}[1]$$

where Cs is soil carbon stock (ton ha^{-1}); Cc is Carbon content (g kg^{-1}); BD is the soil bulk density (g cm^{-3}); D is the thickness of the soil layer (cm).

All the data gathered were statistically compared using analysis of variance (ANOVA) at a 5% level of significance. Those variables that were significantly different were further compared using Duncan's Multiple Range Test (DMRT) at a 5% level of significance. All the statistical computations were computed using CoStat version. 6.4 (CoHort Software).

3. RESULTS

The initial soil properties in this study were slightly acidic ($pH-H_2O$), and the soil had a moderate level of salinity. The soil also contains low amounts of organic carbon, nitrogen, and cation exchange capacity (Table 1).

The ANOVA showed that the interaction between soybean varieties and fertilizer inputs has a significant effect on potassium solubilizer population, phosphate solubilizer population, AMF population, and nitrogen content in the tissue. Meanwhile, the organic carbon, carbon stock, phosphorus content in tissue, potassium content in tissue, seed weight per plant, and seed weight per plot were affected by fertilizer inputs (Table 2).

Table 1. Soil properties at the study site

Soil property	Value
$pH-H_2O$	6.05
pH-KCl	5.87
Electrical conductivity	2.2 ds m^{-1}
Organic carbon	1.39%
Total nitrogen	0.20%
Exchangeable phosphorus	4.79 ppm
Exchangeable potassium	0.18 me 100 g $soil^{-1}$
Cation exchange capacity	14.67 me 100 g $soil^{-1}$

Table 2. Summary of analysis of variance

Observation Variables	Calculated F Value		
	Soybean Varieties	Fertilizer Inputs	Interaction
Organic Carbon	0.41 ns	6.05*	0.40 ns
Carbon Stock	0.72 ns	6.38*	0.50 ns
Potassium Solubilizer Population	28.15 *	5.05*	4.07 *
Phosphate Solubilizer Population	0.04 ns	9.91*	3.86 *
AMF Population	28.74 *	47.31*	31.77 *
Nitrogen Content in Tissue	9.33 ns	3.56*	6.40 *
Phosphorus Content in Tissue	2.09 ns	3.45*	3.03 ns
Potassium Content in Tissue	2.05 ns	3.66*	2.93 ns
Seed Weight per Plant	0.01 ns	4.56*	1.14 ns
Seed Weight per Plot	0.57 ns	6.24*	1.76 ns

Notes = * significant different at $p < 0.05$, ns = not significant different at $p \geq 0.05$

Table 3. Effect of the combination of soybean varieties and fertilizer inputs on the populations of phosphate solubilizers, potassium solubilizers, and AMF

Treatment	Phosphate Solubilizers Population (cfu gr^{-1})	Potassium Solubilizers Population (cfu gr^{-1})	AMF Population (spores 100 gr^{-1})	Nitrogen Content in Tissue (%)
V1P1	21.25 d	25.89 b	10.50 c	1.28 d
V1P2	48.10 ab	39.43 a	26.00 b	1.84 bc
V1P3	46.49 ab	31.76 b	22.00 bc	2.31 a
V1P4	40.88 bcd	29.09 b	30.25 b	1.92 ab
V2P1	23.67 cd	27.01 b	22.75 bc	1.48 bcd
V2P2	43.48 abc	28.29 b	94.25 a	1.30 d
V2P3	31.55 bcd	27.28 b	32.50 b	1.32 d
V2P4	63.92 a	28.88 b	31.50 b	1.39 cd

Notes: Values with the same letter at the same column show that they are not significantly different at 5% in the DMRT test. V1 = Anjasmoro, V2 = Dering I, P_1 = Recommended inorganic fertilizer, P_2 = AMF + *Bradyrhizobium* + potassium solubilizing, P_3 = Phosphate solubilizing + *Bradyrhizobium* + potassium solubilizing and P_4 = Bioenzyme

The interaction between soybean varieties and fertilizer inputs (Table 3) showed that the Dering 1 variety treated with bioenzymes (V2P4) produced the highest phosphate-solubilizing population. This indicates that the use of bioenzymes can enhance the activity of phosphate-solubilizing microbes around the plant roots, contributing to the increased availability of phosphorus that is essential for plant growth. Additionally, the Anjasmoro variety inoculated with the biofertilizer AMF + Bradyrhizobium + potassium solubilizing (V1P2) produced the highest potassium solubilizer population. This study also found that the highest nitrogen content in the tissue was produced by the Anjasmoro variety inoculated with biofertilizer comprising phosphate solubilizing + Bradyrhizobium + potassium solubilizing (V1P3).

The fertilizer inputs showed that the application of biofertilizer inoculation, consisting of AMF + Bradyrhizobium + potassium solubilizing (P2), phosphate solubilizing + Bradyrhizobium + potassium solubilizing (P3), and bioenzymes (P4) were significantly different in organic carbon content and carbon stock compare to recommended inorganic fertilizer (P1) (Table 4). Although there is no significant difference among the application of biofertilizer inoculation, the application of bioenzymes (P4) showed the highest content of organic carbon and carbon stock.

The application of biofertilizer inoculation, consisting of a combination of AMF + *Bradyrhizobium* + potassium solubilizing (P2) and phosphate solubilizing + *Bradyrhizobium* + Potassium solubilizing (P3) showed there were no significant differences in phosphorus content in tissue, potassium content in tissue, seed weight per plant, and seed weight per plot compared to the bioenzyme treatment (P4). Although the differences were not significant, the results obtained from the biofertilizer treatments (P2 and P3) and bioenzymes (P4) were higher compared to the recommended inorganic fertilizer treatment (P1) (Table 5).

Table 4. Effect of fertilizer inputs on organic carbon and carbon stock

Fertilizer Inputs	Organic Carbon (%)	Carbon Stock (ton ha^{-1})
P1	2.12 b	50.39 b
P2	3.16 a	77.89 a
P3	3.06 a	75.16 a
P4	3.20 a	77.96 a

Notes:Values with the same letter at the same column show that they are not significantly different at 5% in the DMRT test. P1 = Recommended inorganic fertilizer, P2 = AMF + *Bradyrhizobium* + potassium solubilizing, P3 = phosphate solubilizing + *Bradyrhizobium* + potassium solubilizing, and P4 = Bioenzyme.

Figure 1 shows the populations of phosphate solubilizers, potassium solubilizers, and AMF form a positive linear correlation with carbon stocks.

Table 5. The effect of fertilizer inputs on phosphorus content in tissue, potassium content in tissue, seed weight per plant, and seed weight per plot

Fertilizer Inputs	Phosphorus content in tissue (%)	Potassium content in tissue (%)	Seed Weight per Plant (g)	Seed Weight per Plot (kg)
P1	0.29 b	1.50 b	53.98 b	1.41 b
P2	0.36 ab	1.84 a	76.59 a	1.76 a
P3	0.39 a	1.99 a	86.79 a	1.88 a
P4	0.37 a	1.92 a	71.03 ab	1.66 a

Notes: Values with the same letter at the same column show that they are not significantly different at 5% in the DMRT test. P1 = Recommended inorganic fertilizer, P2 = AMF + *Bradyrhizobium* + potassium solubilizing, P3 = phosphate solubilizing + *Bradyrhizobium* + potassium solubilizing, and P4 = Bioenzyme.

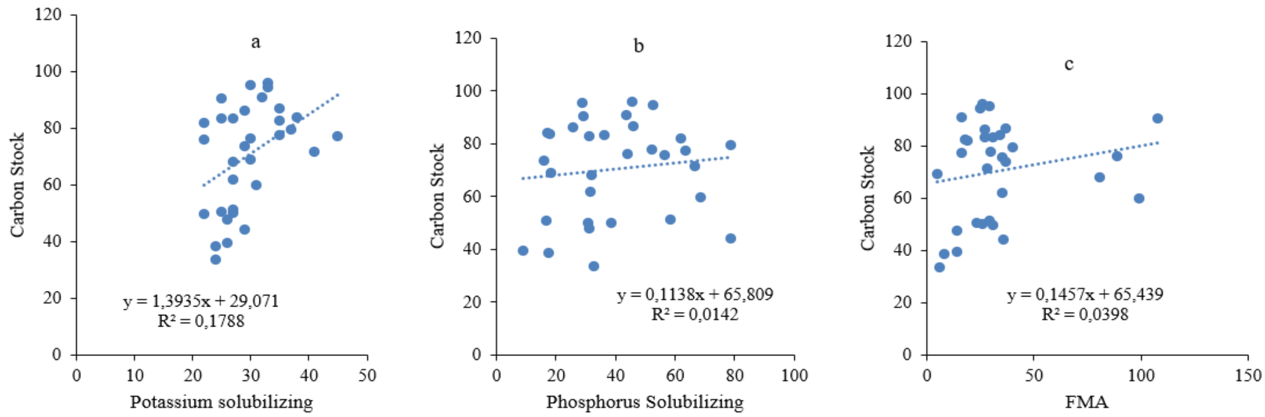

Figure 1. Correlation between soil carbon stock with potassium solubilizing population (a) phosphorus solubilizing population (b), and AMF population (c)

These findings suggest that an increase in the number of solubilizing microbial populations can contribute to an increase in carbon stocks in the soil, which is an important aspect of maintaining soil fertility and mitigating climate change. Among the three types of microbes, the population of potassium solubilizers has a greater influence on carbon stocks, with an R^2 value of 0.1788, indicating that approximately 17.88% of the variation in carbon stocks can be explained by the variation in potassium solubilizer populations. Meanwhile, the AMF population shows an R^2 value of 0.0398, indicating a smaller contribution, and the phosphate solubilizer population has the lowest influence with an R^2 value of 0.0142.

Meanwhile, the soybean yield for both varieties shows that the yield projections exceeded their potential yield based on plant descriptions (Table 6). The Anjasmoro variety showed an increased yield of up to 2.92 tons ha^{-1}, representing a 29.78-43.84% increase compared to its described yield of only 2.03-2.35 tons ha^{-1}. Meanwhile, the Dering I variety recorded a projected yield of 3.05 tons ha^{-1}, an increase of 7.77% from its described yield of 2.83 tons ha^{-1}.

4. DISCUSSION

In this study, the use of biofertilizers and bioenzymes significantly promotes the storage of soil carbon relative to recommended inorganic fertilization applications. This can be implied as meaning the efficacy of the use of biofertilizer inoculation towards boosting organic carbon content and the storage of carbon equals that of applying bioenzymes. Biofertilizers work by increasing the soil biological properties, enabling the activity of microorganisms that are involved in processes of mineralization and carbon fixation in the soil, resulting in increased content of the soil organic matter (Just et al., 2024). Bioenzymes are involved in accelerating the decomposition of plant residues and other organic materials to contribute to soil organic carbon levels. This not only enhances the level of nutrients available for plants but also the characteristics of the soil, just like the application of biofertilizers to enhance soil fertility naturally (Cui et al., 2023). This condition is different from inorganic fertilizers, which tend to provide nutrients directly to plants but do not support increased biological activity in the soil, making them less effective in enhancing soil carbon stocks. Therefore, the use of biofertilizers can be a more sustainable alternative in maintaining soil fertility and supporting climate change mitigation efforts through the enhancement of carbon stocks in agricultural lands (Zheng et al., 2024). On the other hand, the Anjasmoro and Dering 1 soybean varieties produced similar organic carbon levels and carbon stocks. This suggests that both varieties have relatively equal abilities in storing organic carbon in the soil, which is linked to nutrient absorption rates and the decomposition of organic materials in agricultural land. In general, soil organic carbon content can be influenced by plant genetics, climate, and land use practices (Uddin et al., 2022). The carbon stock increase is linked directly to the enhanced activity of soil microorganisms. The result of the study indicates that the populations of phosphate solubilizers, potassium solubilizers, and Arbuscular Mycorrhizal Fungi (AMF) are positively correlated with the carbon stock.

Table 6. Comparison of soybean yields with potential yields based on variety descriptions

Soybean Varieties	Yield Projections (ton ha^{-1})	Yield Potential (ton ha^{-1})*	Yield Improvement (%)
Anjasmoro	2.92	2.03-2.25	29.78-43.84
Dering I	3.05	2.83	7.77

Note: * = potential yield based on plant description

It is a sign that the growth in the number of solubilizing microorganisms can enhance carbon sequestration of soil, and it is an important factor to consider for the maintenance of fertility in the soil as well as in the fight against climate change. This study's results align with previous research, which showed that potassium solubilizers can help boost the activity of other microbes involved in carbon absorption (El-Egami et al., 2024). Additionally, the good population density-carbon stock correlation highlights the substantial role played by mycorrhizae in the enhancement of carbon retention. It has been amply documented that AMF has a positive role to play in strengthening soil structure as well as enhancing water and nutrient uptake, and all of these are geared towards the building of soil carbon storage. By establishing symbiotic relationships with plant roots, arbuscular mycorrhizal fungi (AMF) enhance the transfer of essential nutrients, such as phosphorus and nitrogen, which stimulate plant growth and the accumulation of soil organic matter (Hawkins et al., 2023; Li et al., 2024).

The findings of this study underscore the crucial importance of soil and microbial management in coastal regions, which are especially susceptible to climate change effects, including rising sea levels and environmental pollution. Effective management strategies can enhance soil resilience, improve nutrient cycling, and mitigate the adverse impacts of climate variability, ultimately supporting sustainable agricultural practices in these fragile ecosystems. Soil carbon sequestration serves as a key mitigation strategy by reducing carbon dioxide (CO_2) emissions, a major greenhouse gas contributing to global warming. Enhanced carbon sequestration through photosynthesis and microbial activity can significantly lower atmospheric CO_2 levels, thereby mitigating the effects of climate change. Therefore, effective soil and microbial management in coastal farming systems is essential not only for improving soil fertility but also for contributing to long-term climate change mitigation (Khan et al., 2023; Rodrigues et al., 2023). Increasing plant biomass through the use of biofertilizers and solubilizing microbes also improves overall ecosystem health. For example, the use of phosphorus and potassium-solubilizing microbes can enhance nutrient availability, which in turn boosts crop productivity. This is particularly crucial in coastal areas, which often experience soil degradation due to human activities and environmental changes. By enhancing soil fertility and promoting sustainable agricultural practices, biofertilizers and microbes contribute to long-term soil health, support biodiversity, and help build resilience in these vulnerable ecosystems (Just et al., 2024).

The research findings indicate that microbial activity in the rhizosphere of the two soybean varieties responded differently to the treatments applied. The Dering 1 variety, treated with bioenzymes, resulted in the highest population of phosphate-solubilizing microorganisms. This suggests that the use of bioenzymes can enhance the activity of phosphate-solubilizing microbes around the plant roots, thereby increasing the availability of phosphorus, which is crucial for plant growth. Meanwhile, the Anjasmoro variety, inoculated with biofertilizer AMF + Bradyrhizobium + potassium solubilizing microbes, resulted in the highest populations of potassium solubilizing microbes and Fungi Mikoriza Arbuskular (FMA). This suggests that the activity of these microbes is synergistic, leading to increased availability of phosphorus and potassium in the soil, which in turn enhances plant growth and overall productivity (Burak et al., 2024; El-Egami et al., 2024).

In general, inorganic fertilizers lead to lower populations of phosphate-solubilizing microorganisms, potassium-solubilizing microorganisms, and AMF compared to the use of biofertilizers and bioenzymes. While inorganic fertilizers supply nutrients directly to plants, they do not promote the growth and activity of beneficial microorganisms that play a crucial role in maintaining soil ecosystem sustainability. In contrast, biofertilizers and bio enzymes enhance microbial diversity and activity, supporting nutrient cycling processes and long-term soil health (Prisa et al., 2023) and may even lead to a decrease in microorganism populations (Setiawati et al., 2023). Several previous studies have demonstrated that the application of nutrient-solubilizing microbes can significantly enhance nutrient availability, leading to increased crop productivity and contributing to the sustainability of agricultural systems (Kumar et al., 2024; Mahmud et al., 2021). With increasing focus on sustainable agriculture, the use of biofertilizers and bio enzymes is becoming increasingly relevant in land management strategies aimed at improving soil fertility, minimizing dependence on chemical fertilizers, and reducing the environmental impacts of conventional agricultural practices (Chaudhary et al., 2022).

Based on the research results, it appears that the increased activity of soil microorganisms has a positive impact on nutrient absorption. The highest nitrogen content in tissues was found in the Anjasmoro variety inoculated with a biofertilizer composed of phosphate solubilizers + Bradyrhizobium + potassium solubilizers. Bradyrhizobium assists in the biological fixation of nitrogen from the atmosphere, providing essential nitrogen for plant growth. Meanwhile, phosphate solubilizers dissolve bound phosphorus in the soil, enhancing its availability and supporting enzymatic activity as well as energy synthesis related to nitrogen assimilation. Potassium solubilizers increase the availability of potassium, which plays a role in osmotic regulation and ion balance, thereby improving nitrogen use efficiency. The combination of these microbes showed a positive linear correlation with increased nitrogen content in plant tissues. Previous studies have indicated that the use of these microbes can enhance nitrogen fertilizer efficiency, reduce the need for chemical fertilizers, and improve the sustainability of agriculture. Thus, these three microbes work synergistically to enhance nitrogen absorption and plant productivity, while also supporting more environmentally friendly agricultural practices (Ladha et al., 2022; Sharma et al., 2024; Suleimanova et al., 2023).

The research results show that the phosphorus content in plant tissues, the potassium content in plant tissues, seed weight per plant, and seed weight per plot in both Anjasmoro and Dering 1 varieties are equally good. This indicates that both varieties have similar nutrient absorption capabilities, resulting in comparable seed yields. The lack of significant differences in these parameters is most likely due to the genetic characteristics of both varieties, which lead to similar responses to nutrient availability and other agronomic factors (Shahin et al., 2023). Previous studies have reported that the genetic factors of a variety influence nutrient absorption and the efficiency of nutrient utilization. However, in some cases, environmental factors and land management practices tend to play a more dominant role in determining crop yields (Dhingra et al., 2024). In addition, the homogeneity of soil conditions, fertilization, and land management can also contribute to uniform harvest outcomes across varieties. When environmental factors, such as water and nutrient availability, are consistent, plants from different varieties tend to show similar results in certain parameters, even though there may be slight genetic differences in nutrient absorption efficiency (Sivaram et al., 2023).

The application of biofertilizer and bioenzyme inoculants was also found to increase the phosphorus and potassium content in plant tissue, seed weight per plant, and seed weight per plot compared to the recommended inorganic fertilizer treatment. It implies that both biofertilizers and bioenzymes are more efficient at enhancing the absorption of major nutrients, namely phosphorus and potassium, compared to the application of traditional inorganic fertilizers. The increased absorption of P and K with the use of biofertilizers can be attributed to the activity of helpful soil microbes, such as Bradyrhizobium, that facilitate nitrogen fixation, and phosphate and potassium solubilizing organisms that facilitate the availability of these nutrients in the soil. The AMF also possesses the ability to boost the plant root networks and hence improve the ability of the plant to uptake the nutrients from the soil (Alamzeb et al., 2024; Kuila & Ghosh, 2022). The use of biofertilizers and bioenzymes also has the potential to improve the sustainability in agriculture since they not only improve the production of the crops but also contribute towards the betterment of physical, chemical, and biological characteristics of the soil. These practices are an environmentally friendly alternative to the intensive use of chemical fertilizers, which have the tendency to degrade soil and pollute the environment. Through the generation of healthier soils and the reduction of dependency on chemical inputs, bio enzymes and biofertilizers facilitate long-term soil fertility and a more sustainable agricultural system, ensuring productivity with fewer ecological impacts (Barbosa et al., 2021). Biofertilizers are widely recognized for their ability to enhance plant tolerance to salinity stress, primarily by mitigating oxidative stress through the reduction of antioxidant levels in plants (Dullah et al., 2019). Salinity stress triggers the formation of free radicals in plant cells, which can destabilize cell membranes and interfere with vital metabolic functions. The application of biofertilizers, which contain beneficial live microorganisms, has been shown to stimulate antioxidant enzyme activity, thereby reducing oxidative stress and strengthening plant resistance to saline conditions (Liu et al., 2022; Narayan et al., 2024). Moreover, biofertilizers contribute to plant resilience by producing key phytohormones (Sodiq et al., 2021). These phytohormones play a crucial role in promoting root development, enhancing water and nutrient uptake efficiency, and supporting the overall physiological stability of plants affected by salt stress. Consequently, plants treated with biofertilizers can maintain optimal growth and productivity even under challenging environmental conditions (AbuQamar et al., 2024; Mishra et al., 2021).

In general, the research results show that both soybean varieties, Anjasmoro and Dering I, have projected yields that exceed the potential yields based on plant descriptions. This increase in yield indicates that the use of biofertilizers and bioenzymes plays an important role in enhancing nutrient uptake by the plants, contributing to increased productivity. The use of biofertilizers containing microbes such as Bradyrhizobium, AMF, phosphate-solubilizing bacteria, and potassium-solubilizing bacteria has proven effective in increasing the availability of essential nutrients such as nitrogen, phosphorus, and potassium in the soil. These microbes work synergistically with bioenzymes to improve nutrient uptake efficiency by the plants, thereby enhancing growth and seed yield. Previous studies also support that inoculation with nutrient-solubilizing microbes can increase plant productivity by improving soil fertility and nutrient use efficiency (Bertham et al., 2020; Soumare et al., 2023). In addition, bio enzymes play a role in facilitating the decomposition of organic matter, thereby releasing nutrients that are available to plants and supporting land productivity, especially in soils with low fertility or in coastal soils facing environmental stresses such as high salinity (Yu et al., 2023).

Soybean farming greatly benefits from soil carbon sequestration as it enhances soil fertility, nutrition, and water-holding capacity (Urrutia Larrachea et al., 2024). Higher organic carbon levels promote soil microbial processes such as nitrogen fixation and organic matter decomposition, and thereby release the required nutrients like nitrogen, phosphorus, and potassium for the normal development of soybean. The organic carbon content also serves as a source of energy for beneficial microorganisms in the soil, stimulating them to become more active and making the process of nutrient cycling in the soil ecosystem more efficient. In this way, there is a continuous supply of nutrients, rendering synthetic fertilizer less required and resulting in more sustainable agriculture. In addition, the increased soil carbon level improves the soil structure through the process of increased soil aggregation that leads to better aeration and root penetration and also increases cation exchange capacity (CEC) for improved nutrient retention and reduced leaching of nutrients (X. Wu et al., 2022). Furthermore, soils with higher carbon content exhibit superior water retention, which is particularly beneficial in regions with fluctuating rainfall patterns or prolonged dry spells, ensuring stable crop growth and yield consistency. Studies have shown that soybean seed yields from soils with higher carbon content can be significantly greater than those from soils with lower carbon levels, underscoring the essential role of carbon in supporting crop productivity (Faé et al., 2020; D. Wu et al., 2022).

5. CONCLUSION

Biofertilizers and bioenzymes have been proven to enhance soil carbon reserves. The population of potassium-solubilizing microbes has a greater influence on carbon stocks compared to the populations of phosphate-solubilizing microbes and AMF. The application of biofertilizers and bioenzymes also improves the biological properties of the soil, contributing to increased soybean yields. The soybean varieties Anjasmoro and Dering I have comparable yields, with projected results exceeding their descriptive yield potential. Future research can focus on optimizing the combination of biofertilizers and bioenzymes to enhance carbon sequestration efficiency across various soil types and agroecological conditions. Long-term evaluation of carbon stock dynamics and its impact on soybean productivity is also necessary to ensure the sustainability of biofertilizer- and bioenzyme-based agricultural systems.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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